10. DIRECT ENERGY CONVERSION

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In NASA space-power-generation work, considerable emphasis has been placed on direct energy conversion. This is an advanced technology which is of interest though not necessarily of immediate usefulness to industry. Direct-energy-conversion methods are those methods by which energy from the sun, a nuclear reactor, or a chemical reaction can be converted directly to electricity. Four types of direct-conversion processes are discussed: electrochemistry, thermoelectrics, thermionics, and magnetohydrodynamics, more commonly called MHD.

ELECTROCHEMISTRY

Traditionally, the energy in coal and petroleum fuels is released as heat by burning the fuel. This heat is then used to power a mechanical generating system. In an electrochemical process, this heat-production step is avoided, and a large part of the energy in the fuel appears directly as electricity.

There are two types of electrochemical energy converters: the familiar storage battery and the fuel cell. In a battery, the reacting chemicals, one a fuel and the other an oxidizer, form the negative and positive electrodes within the case. These electrodes participate in the energy-producing reaction. The products formed by the reaction are likewise stored within the battery, so that the composition of the active materials within the container changes as energy is generated. A battery continues to operate until all the reactants contained on the electrodes are used up, after which it must be recharged or discarded.

A fuel cell differs in that the reacting chemicals are stored outside the case and are fed to the electrodes when energy is to be produced. The electrodes serve only as reaction sites and current carriers. The products of the reaction are removed as rapidly as they are formed so that there is no net change in the composition of the material within the case. As a result, energy can be generated as long as reactants are supplied and products are removed.

Batteries are well known for their ability to store energy. Energy storage is particularly important in space, since virtually every function performed by a spacecraft is initiated or controlled by electricity which must be generated or stored onboard. Ideally then, batteries for space must be light, have long service lives, be sealed to operate in vacuum, and in some cases, must withstand rapid recharging.

At present, most spacecraft energy storage needs are met by rechargeable batteries. Battery performance characteristics are shown in table 1-I. The available theoretical and actual energy densities are listed as well as the battery life in terms of the number of charge-discharge cycles delivered when 25 percent of the rated output is used during each discharge. The nickel-cadmium battery, while lowest in both theoretical and actual energy density, and therefore the heaviest of the space batteries shown, can deliver well over 10 000 cycles in low-altitude earth orbit. While only slightly better on a theoretical basis, the more favorable design features of the silver-cadmium system allow a significant increase in energy density but only about one-third the life. The silver-zinc battery offers major improvements in both theoretical and actual outputs. However, problems discussed later presently limit the life to 400 cycles. For comparison, the lead-acid traction battery is shown. While it is comparable to nickel-cadmium on a weight basis, it has the life characteristics of the silver-zinc system for this type of service.

NASA battery technology programs seek to improve each of these three space battery types. In addition, new kinds of batteries are being developed for service under extremes of temperature and to produce much higher energy outputs per pound.

This discussion is confined to work on zinc-electrode batteries because they have been prominently mentioned for electric vehicle use, and electric vehicles are a potentially interesting market area for the utilities industry.

Zinc-battery research is being performed by NASA in the following areas: silver-zinc cell development, zinc electrode structure, organic electrolyte, and the zinc-oxygen cell.

For the past 3 years, NASA has supported the development of a long-life rechargeable silver-zinc cell which makes use of a novel inorganic separator material to hold the electrolyte between the electrodes. The performance characteristics of this cell are shown in figure 10-1. Cycle life at 25 percent depth of discharge is shown as a function of operating temperature. The new cell delivers 5 to 7 times the life of the standard cell at room temperature and can operate over a much broader temperature range. The life of this cell is now limited by zinc-electrode problems, rather than separator-related failures. Testing is presently

underway on new zinc-electrode compositions and structures which have given as much as twice the life of the zinc electrodes used in the experimental cells (fig. 10-1).

Major increases in energy density are possible through the use of highly energetic reactants. These require stable organic liquids for electrolytes in contact with highly reactive electrodes. The most common fuel electrode in use is lithium metal, while zinc is one of several elements whose compounds look interesting as oxidizers. A nonrechargeable lithium - copper-fluoride cell which performs well over a limited range of temperatures and discharge rates has proved successful. However, the development of a rechargeable organic electrolyte battery is a much more difficult technical problem, and at present no organic electrolyte battery exists which is suitable for either space or electric vehicle use.

A sealed zinc-oxygen battery presently under development could be attractive for ground as well as space use because it solves one of the major problems of the zinc-air combination, namely the need to purify the incoming air by removing carbon dioxide and other harmful contaminants. This is a new program in which know-how obtained while developing a rechargeable hydrogen-oxygen battery is combined with the zinc electrode and cell work described earlier.

It is appropriate at this point to direct a few specific remarks to the subject of batteries for electric vehicles, since this is a potentially significant application for advanced battery technology work. Many studies have been made to decide what kind of battery is best suited for this application. As is the case for space batteries, it must be light, compact, and efficient, and in addition, must be inexpensive. Specific comparisons have been drawn in a number of ways. Figure 10-2, taken from the 1967 Department of Commerce study entitled "The Automobile and Air Pollution," shows the specific power produced by the battery as a function of the energy density obtained for a particular set of vehicle specifications and operating conditions. In general, the usefulness of a battery for vehicle propulsion increases as both of these values increase. While other studies use different assumptions regarding vehicle size and performance, the relative positions of the various systems shown do not change significantly.

However, performance is not the only criterion for judging vehicle batteries. Because the installed power supply may reach 50 kilowatts and 50 to 100 kilowatt-hours, considerable quantities of materials are involved, and cost and availability are important. Table 10-II shows raw material and availability data for classes I, II, and III of systems shown in figure 10-2.

Despite its poor performance, the lead-acid battery offers acceptable costs and fair availability of raw materials. These features make it suitable for some

limited motive power uses such as golf carts and forklift trucks. Nickel-cadmium and nickel-zinc batteries have performance characteristics that look adequate for the delivery-van type of vehicle. Unfortunately, raw materials for the nickel-cadmium battery cost twice as much as those for the lead-acid battery, and the supply of cadmium is poor in terms of large-scale vehicle use. On the other hand, the raw material costs for the nickel-zinc battery are comparable to those for the lead-acid battery, and a distinct performance advantage has been demonstrated. These factors coupled with the availability of raw materials have led to renewed interest in the nickel-zinc battery in recent years.

The silver-zinc and zinc-air batteries seem suitable for some specific-purpose passenger cars, although the range, speed, and acceleration may be somewhat less than desired. Silver-zinc can readily be dismissed on the basis of the price and the limited supply of silver available. The zinc-air combination is the one receiving major attention today. The cost of zinc and its availability, coupled with the anticipated performance, make this battery look very attractive. However, in assessing this system, one cannot overlook the need for a precious-metal catalyst for the air electrode. Based on current technology, a figure of $500 per kilowatt for the catalyst alone is not unreasonable. Earlier it was stated that a vehicle battery may require 50 kilowatts of installed power. Clearly, such electrodes are economically unattractive, and a successful low-cost air electrode will be required before this system can be a serious contender for vehicle propulsion.

Much better performance would be possible with development of the class IV systems, shown in table 10-II, namely, sodium-sulfur, lithium-chlorine, and organic-electrolyte batteries. These couples offer the greatest promise for electric vehicles. The raw materials are inexpensive and available. However, these are advanced systems, all of which have difficult technical problems still to be solved. These kinds of technologies will not be easy to develop, but they are the ones that seem to offer the greatest promise for a publically acceptable, wholly battery-powered car.

While batteries are of interest as a means for storing energy, fuel cells hold a different attraction. Conversion efficiencies of 45 to 65 percent make the fuel cell, in theory, a contender for a central station power. This application, in fact, spurred fuel-cell research at the turn of the century, but the successful development of the steam turbine power cycle greatly reduced that research effort. Interest was rekindled by the work of Bacon in England in the 1930's and increased in the 1950's under both Government and private support of research. It is the space program, however, which produced the first real application of a fuel cell wherein its uniquely high efficiency was a key factor in its selection. The most

advanced fuel cells and fuel-cell systems that exist today are those built for the space program.

Figure 10-3 shows the assembly of a Gemini fuel-cell power system. This system, built by the General Electric Company, was used on seven Gemini flights. The three 24-volt fuel-cell stacks which make up one power system are shown just prior to being assembled into their container. Two complete power systems were carried on the spacecraft, each delivering 120 to 640 watts.

The Apollo fuel-cell system, shown in figure 10-4, delivers 600 to 1400 watts from a single 28-volt fuel-cell stack. Three powerplants of this type built by Pratt & Whitney Aircraft will be carried aboard the Apollo spacecraft. To date, the system has been flight qualified and was flown during unmanned tests. A third system, designed and built by the Allis-Chalmers Manufacturing Company, has been developed to the point where it is ready for flight qualification testing.

Each of these systems is different in terms of the cell design, electrolyte, operating temperature and pressure. However, as these systems exist today, their characteristics can be summarized as follows: Hydrogen-oxygen fuel-cell systems have an overall efficiency of 50 to 60 percent. While single cells have run for a year or more, the expected life of a complete system is only 1000 to 3000 hours. Costs are high, with $25 000 to $50 000 per kilowatt typical today. Obviously, for a commercial fuel cell, this lifetime is too short, costs are too high, and the attractive efficiency is only available when hydrogen is used as the fuel. Basically, three problems confront the development of a commercial fuel cell. Lifetimes of 20 to 40 years are desired, as are low capital costs, and efficiencies of 50 percent or more must be obtained from inexpensive fuels. The problems of life, efficiency, and cost can all be related to the existing requirement to use precious metals such as platinum, silver, gold, or palladium in the fuel-cell electrode, structure, or system. The major cost elements for several commercial fuel cells, capable of operating over a number of temperature ranges, are shown in table 10-III along with remarks pertaining to significant problems of each type. For all low-temperature fuel cells in use today, platinum or silver must be used to catalyze the air-electrode reaction. Platinum has also been the most effective fuel-electrode catalyst. As a result, catalyst costs are very high, and the supply of platinum is so limited that even if it were feasible to use catalyst loadings of only 10 percent of the currently effective quantities, the large-scale use of fuel cells would still be impossible.

The electrochemists offer a seemingly simple solution to this problem, namely, to raise the operating temperature to the point where expensive catalysts

are no longer required. Indeed, higher temperature cells are being operated without the presence of precious metal catalysts. However, these expensive materials do not really disappear as expected but appear in other forms in the fuel cell or system. For example, moderate-temperature fuel cells can be catalyzed by nickel and nickel oxide but require pure hydrogen to maintain their efficiency. The purifier, made of a palladium-silver alloy is either made a part of the electrode or appears as a separate system component. This purifier may cost as much as the fuel cell itself. For intermediate- or high-temperature cells, expensive materials appear in electrode structures or cell components, not for their catalytic properties, but because of their inherent corrosion resistance and electrical conductivity. As a result of using these materials and the specialized construction methods required for elevated-temperature devices, costs are expected to be very high. Demonstrated efficiencies have been below those of lower temperature cells, and the maximum attainable may be only 40 percent from inexpensive fuels.

The conclusion is that new catalyst technology, in terms of finding less expensive materials and making more effective use of the present expensive ones, is required. Toward this end, NASA-sponsored research is being conducted on the nature and site of the key reaction processes within the electrodes, on improvement of the electrode structures themselves, and on the synthesis and testing of entirely new materials as catalysts. It is clear that the fuel cell cannot be competitive without a new technological invention. Should such an invention come into being, however, the fuel cell could be a serious candidate almost overnight. There is no way of predicting when this may occur, but there is likewise no reason to think that it is impossible.

THERMOELECTRICS

Like the battery and the fuel cell, the origins of thermoelectricity date back to the early 1800's. In 1820, Seebeck was working with an electrical circuit made of dissimilar materials and found that a voltage was developed in the circuit when one of the junctions was heated. Attempts were made to generate electrical power using this effect shortly after its discovery. With the materials available at that time, the conversion efficiency was less than 1 percent. Relatively little progress was made in thermoelectricity during the following century. Finally, in the mid-1950's, when an understanding of the behavior of semiconductor materials was acquired, interest was focused on generator development.

As shown in figure 10-5, thermoelectric couples now make use of a negative or N-type and a positive or P-type semiconductor element. The elements are

connected at one end through what is called a hot shoe. The point of contact between each element and the hot shoe is called the hot junction. The open end of the couple is called the cold junction, and the elements are connected through the electrical load at the cold end. Heat is applied to the hot shoe and flows through the elements. A fraction of this heat is converted directly into electricity. The unconverted, or waste, heat is rejected at the cold junction.

Semiconductors are used for energy conversion because they offer the best compromise between the voltage that can be developed in the current and the temperature difference that can be maintained across the elements.

A couple fabricated by RCA and being used in a program at Lewis is presented in figure 10-6. Silicon-germanium (Si-Ge) elements are used in the form of half cylinders. The hot shoe is a silicon-molybdenum alloy. Electrical leads are bonded to the elements and a stud is provided for mounting the couple on a support plate. The hot shoe measures 1.1 inches on a side and the elements are 0.4 inch long.

The couple was designed to operate at a hot-junction temperature of 1500° F and a cold-junction temperature of 800° F. The conversion efficiency is 3.5 percent and the power output is 0.3 watt. The high cold-junction temperature was selected so that waste heat could be rejected to space by radiation.

The performance could be improved by reducing the cold-junction temperature, as illustrated in table 10-IV, where the maximum useful temperature and the efficiency which can now be realized in ground applications are listed for the three most commonly used materials, bismuth telluride (BiTe), lead telluride (PbTe), and Si-Ge. The efficiency is based on the hot junction being at the maximum useful temperature and a cold-junction temperature of 100° F.

Bismuth telluride can be operated at a maximum hot-junction temperature of 500° F, resulting in an efficiency of 6 percent. Lead telluride, which has seen the most use to date in this country, can be operated at a temperature of 1000° F with a corresponding efficiency of 10 percent. The third material, Si-Ge, is not as efficient as the tellurides when operating over the same temperature range, but can be used at much higher temperatures (1800° F), also resulting in an efficiency of 10 percent.

These efficiencies are quite low, but the important point is that the efficiency is independent of power output. These values can be achieved at a power output of a fraction of a watt, and thermoelectrics have been used at low power levels in space and on the ground.

Five radioisotope-heated generators have been operated in space at power levels up to 25 watts, and several, more advanced generators will be used in future missions. For example, the SNAP-27 generator, shown in figure 10-7, is to

be used in the Apollo program for powering experiments on the lunar surface. The generator produces 56 watts of electrical power. The cylindrical radioisotope heat source contains plutonium fuel. Lead telluride couples, about the same size as the Si-Ge couple shown in figure 10-6, are arranged around the heat source. Waste heat is conducted from the couple cold junctions to the outer shell of the generator and is radiated to space from a series of metal fins. The generator weighs 46 pounds and, like its predecessors, is quite compact, measuring 18 inches long and 15 inches across the fins.

In addition to the isotope-heated generators, there has also been one nuclear-reactor thermoelectric system operated in space, the SNAP-10A, which used Si-Ge couples and produced a power output of 500 watts.

On the ground, thermoelectrics have been used only in special applications. As an example, PbTe couples have been used for many years as sensors in the safety control system in gas furnaces.

Radioisotope and propane-heated generators have been used at power levels of 100 watts or less in a number of applications, including powering automatic weather stations in remote areas, powering deep ocean navigational aids, etc. In all these applications, thermoelectric generators proved to be very reliable.

Whether or not thermoelectrics will eventually be used at much higher power levels depends entirely on improvements in efficiency. The three main technology areas being pursued with the objective of improving efficiency are materials research, materials optimization, and cascaded materials. Programs in these areas are supported principally by the Atomic Energy Commission and by NASA.

Research programs directed toward the development of improved thermoelectric materials have been in progress for several decades. This activity led to the discovery of the telluride class of materials in the mid-1950's and Si-Ge in 1960. No better materials have been found since 1960 and the lack of positive experimental results is now being supported by theoretical arguments. Of course, it is impossible to predict what might happen in a research area, but there may be no better materials than the ones now in use.

An effort is being made to improve the efficiency of existing materials by optimizing their composition and improving the techniques used for bonding the elements to hot- and cold-junction materials. Only modest improvements in efficiency are expected from these efforts.

The cascaded materials program is directed toward improving generator efficiencies by using two or possibly all three available materials in a single generator with each material operating over the temperature range in which it is most efficient. With the development of cascaded generators, the maximum thermoelectric efficiency for ground applications should approach 15 percent. At this level, ther-

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moelectrics will not be a major power system. But, the couples are simple and very reliable and will certainly continue to be used in applications where small amounts of power are required for moderately long periods of time.

THERMIONICS

In contrast to thermoelectrics, thermionics is of principal interest at power levels ranging from tens of kilowatts to tens of megawatts. Thermionic conversion is based on the fact that electrons are emitted from a hot metal surface. As shown in figure 10-8, a thermionic converter consists basically of two electrodes separated by a small gap. One electrode, the emitter, is maintained at a high temperature. The second electrode, the collector, is maintained at a lower temperature. When heat is added to the emitter, electrons escape and move across the gap to the collector. Part of their energy is given up at the collector in the form of heat which must be rejected. The remainder of their energy is available to do work in the external load as they return to the emitter.

In all practical converters, cesium vapor is introduced into the space between the electrodes. The addition of cesium increases the current flow and also allows the electrons to move across a much wider gap than would be possible if the space were evacuated.

An actual converter is quite a bit more complicated than might be first envisioned for several reasons: (1) even with cesium addition, the interelectrode spacing is limited to values of the order of 0.010 inch; (2) in order to contain the cesium vapor, the electrode system must be surrounded by a leak-tight envelope; (3) a way must be provided to control the cesium vapor pressure, which is critical to the operation of the converter.

A cutaway view of a laboratory test device is presented in figure 10-9. The emitter is the circular disk at the top. The collector is located below the emitter. The cesium vapor pressure is controlled by adjusting the temperature of a pool of liquid cesium located in the reservoir. Cesium vapor occupies the space between the emitter and collector and the space enclosed by the outer envelope. The emitter and collector structures must be electrically isolated, and this is accomplished with an insulating metal-to-ceramic seal.

The high operating temperatures necessary for thermionic conversion require that the emitter and the part of the outer envelope in contact with the emitter be made of refractory metal. In most cases, the remainder of the outer envelope, as well as the collector and the collector support structure, are also made of refrac-

tory metal. Laboratory test devices are typically 1/2 inch in diameter and produce up to 40 watts of electrical power.

The efficiency which is presently being achieved in the laboratory is presented as a function of emitter temperature in figure 10-10. The band shown results from the use of different combinations of electrode materials. The minimum acceptable temperature is 2500° F for which the efficiency is 7 to 10 percent. Increasing the emitter temperature to 3000° F increases the efficiency to 14 to 17 percent. These are not particularly high efficiencies. An interesting point about thermionic conversion is that the efficiency does not increase continuously as the collector temperature, which for this range of emitter temperature is 1400° F. It is the combination of an acceptable efficiency and high heat-rejection temperatures that makes thermionics attractive for high-power space applications. It is quite possible that this same combination may make thermionics of future interest for ground applications as a topping cycle in which the heat rejected by the thermionic system would be transferred to a conventional steam plant.

Considering heat sources, temperatures of 3000° F can easily be achieved by burning a fossil fuel and air. However, refractory metals cannot be exposed to the products of combustion. Some work has been directed toward the use of protective coatings around the converter, but the results to date have not been very encouraging.

Currently, the most interesting heat source for thermionic conversion is a nuclear reactor. Technology programs, directed toward this application, have been supported by NASA, AEC, and other government agencies since the early 1960's. The major technology areas are as follows: converter performance, converter life, and high-temperature fuel.

The objective of the converter-performance program is to reduce the emitter temperature. Encouraging results have been achieved, particularly over the past 2 years, in developing techniques for orienting the crystal axes of tungsten in a particular way. Preliminary data indicate that, for a given efficiency, a reduction in emitter temperature of 200° to 300° F should be possible with these new techniques. This activity is continuing but there are no prospects at present for reducing the required temperature below about 2200° F.

Several converters have been operated continuously for periods of 1 to $1\frac{1}{2}$ years at emitter temperatures of 3000° F. However, these lifetimes are not being consistently achieved. The major cause of converter failure has been loss of cesium through leaks in the outer envelope. Work in this area is directed toward improving metal-to-metal joining techniques and metal-to-ceramic seal structures.

In addition to converter improvements, a nuclear fuel with high-temperature capability is required for the thermionic reactor. The problems involved in this

area were discussed in the paper on nuclear reactors.

In perspective, steady progress is being made in thermionic technology. However, the technology is difficult because of the high temperatures involved and it will be some time before a high performance nuclear thermionic system can be designed with real confidence.

MAGNETOHYDRODYNAMICS

Magnetohydrodynamic (MHD) power generation is quite different from direct-conversion techniques. The MHD generator is, in fact, identical in operating principle to a conventional generator. Instead of a solid conductor, a conducting fluid is used. As shown in figure 10-11, as the fluid flows through a channel at right angles to an applied magnetic field, a voltage is developed across the channel. The fluid may be a liquid metal, a liquid-metal vapor, or a gas.

The highest generator efficiency demonstrated has been 56 percent, which was achieved with a small liquid-metal unit. However, efficiency estimates for very large generators producing hundreds of megawatts of electrical power are 70 to 75 percent. These are efficiencies for the generator only and are not overall system efficiencies.

The performance of an MHD generator depends on three factors: the electrical conductivity of the fluid, the velocity of the fluid, and the strength of the magnetic field. In table 10-V, typical values of the electrical conductivity in mhos per meter, the velocity in feet per second, and the magnetic field strength in kilogauss are presented for a liquid metal and two high-temperature gas systems.

A liquid metal has an electrical conductivity of 10^6 mhos per meter. This value is only 1 percent of the conductivity of copper but is quite adequate for power generation in combination with a velocity of 300 feet per second and a magnetic field strength of 10 kilogauss. A magnetic field strength of 10 kilogauss is within the capability of conventional magnets. The problem with this system is to find an efficient way of accelerating the liquid. Most approaches involve mixing the liquid with a vapor and accelerating this two-phase fluid through a nozzle. Before entering the generator, the vapor is either condensed or removed from the liquid in a separator. Considerable component technology has been developed for liquid-metal systems. With presently available components, the overall efficiency of a liquid system would be less than 10 percent at a peak temperature of 2000° F. Work is continuing on the development of components in which fluid friction effects are less significant and modest efficiency improvements are expected.

In gas MHD systems, the principal problem is achieving acceptable electrical conductivity. Consider first an open-cycle combustion-fired generator. The flame temperature when hydrocarbon and pure oxygen are burned can reach 5000° F. If the products of combustion are seeded, that is, if an easily ionized material, such as an alkali metal vapor, is added to the products of combustion, the conductivity of the gas in the generator would be about 10 mhos per meter. Even this very low conductivity is adequate for power generation in combination with a velocity of 5000 feet per second and a magnetic field strength of 30 kilogauss. The velocity can be easily achieved by expanding the gas through a nozzle. In a practical application, cryogenic cooling would be required for the 30-kilogauss magnet.

Several combustion-fired MHD experiments have been run. As a matter of fact, the feasibility of MHD power generation was demonstrated in a combustion-fired experiment conducted at Westinghouse about 10 years ago. The largest system of this type tested to date was built by the AVCO Corporation under Air Force sponsorship and operated in late 1964. The operating characteristics of the combustion-fired MHD generator are as follows:

Inlet gas temperature, $^{\circ}$F . . . . ~4500
Exit gas temperature, $^{\circ}$F . . . . ~4000
Gas velocity, ft/sec 5600
Magnetic field strength, G 33 000
Gross power, MW_e 32. 6
Net power, MW_e 23. 5

The generator was rocket-driven, burning ethyl alcohol and gaseous oxygen. Potassium seed was used. The system developed a gross power output of 32. 6 megawatts at 20 000 amperes and 1630 volts. Of this, 9. 1 megawatts were supplied to the magnet resulting in a net power output of 23. 5 megawatts electric. Based on net power output and total thermal power input, the overall efficiency of the system was 6 percent. The system was designed to meet an Air Force requirement for high-power pulse operation so that operating times were very short ranging from 10 to 60 seconds.

An overall view of the system is presented in figure 10-12. The combustor and nozzle are on the left. The generator is located in the center section and is enclosed by the magnet. The magnet, which weighed over 70 tons, is supported by heavy steel straps. The generator channel was 10 feet long and 2 feet square at the exit. Products of combustion were exhausted to the atmosphere.

Experiments of this type, in which large amounts of power were generated, prompted considerable interest in the possible use of combustion-fired systems for topping conventional steam plants.

One of the very important questions which remains to be answered is related to life. AVCO tested a small generator channel with flowing combustion products. This test, which ran for 200 hours, is the longest test to data. The channel was in acceptable condition after the test, but much longer life must be demonstrated before combustion-fired systems can be considered for commercial use.

For closed-cycle applications, peak temperatures must be limited to values well below 5000° F. Even if a peak temperature of 3000° F were achievable, the seeded gas in the generator, if ionized thermally, would have an electrical conductivity of only 1 mho per meter and it would finally become impractical to build an MHD generator.

In closed systems, ionization techniques other than thermal must be used to improve conductivity. These techniques involve accelerating electrons to sufficiently high velocities so that the seed material atoms can be ionized by collisions with the electrons.

The approach receiving most attention is one in which electric fields existing within the generator itself are used to accelerate the electrons. At present, this is a basic research problem and is being investigated at Lewis and by other organizations. The generator channel used in the NASA program is shown in figure 10-13. It is now being tested with argon at 3100° F. The generator, which has a volume of 1/4 cubic foot, could theoretically produce 500 kilowatts electric if predicted levels of conductivity can be realized.

Progress toward achieving this so-called nonequilibrium ionization is still in its infancy. Much more research is required before any realistic evaluation of closed-cycle gas systems can be made.

SUMMARY

Of the direct energy conversion methods discussed, the only one which may possibly have an influence on the electric power industry in the relatively near future is the battery. This, however, represents a new market for electricity, rather than a new technique for manufacturing it.

Fuel cells, thermionics, and MHD do represent potential changes in production techniques which could result in lower production costs. For each one of these, deficiencies were indicated, either technical or economic, which make them unattractive in their present state of development. However, as technology continues to be developed in these areas, reassessment of these techniques by the utilities industries will be required.

TABLE 10-I. - RECHARGEABLE BATTERIES FOR SPACE USE

System	Energy density, W-hr/lb		Cycle life at 25 percent depth of discharge
	Theory - reactants only	Actual - complete battery	
Nickel-cadmium	107	12	10 000
Silver-cadmium	120	20	3 000
Silver-zinc	208	40	400
Lead-acid[a]	81	10	400

[a]For comparison.

TABLE 10-II. - COST AND AVAILABILITY OF BATTERY MATERIALS

Class	Battery couple	Raw material cost, $/(kW-hr)	Availability
I	Lead-acid	5.50	Lead: fair
II	Nickel-cadmium Nickel-zinc	10.1 5.30	Cadmium: poor Nickel and zinc: good
III	Silver-zinc Zinc-air[a]	101 .90	Silver: poor Zinc and air: good
IV	Sodium-sulfur Lithium-chlorine Organic-electrolyte	1.08 2.80 3.41	Sodium and sulfur: excellent Lithium: good Lithium: good

[a]$500/kW for catalyst alone.

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TABLE 10-III. - MAJOR COST ELEMENTS FOR COMMERCIAL FUEL CELLS

Temperature, $^\circ$F	Temperature range	Material	Use	Cost, $/kW	Remarks
200	Low	Platinum, silver	Catalyst	500 to 1000	Limited supply
300 to 450	Moderate	Palladium, silver	Hydrogen purifier	120	Limited supply
1000 to 1500	Intermediate	Platinum, silver	Electrodes	200	Corrosion; low efficiency
1800	High	Several	Cell parts	High	Fabrication; low efficiency

TABLE 10-IV. - THERMOELECTRIC MATERIAL CHARACTERISTICS

Material	Maximum useful temperature, $^\circ$F	Efficiency (cold-junction temperature, 100° F), percent
Bismuth telluride	500	6
Lead telluride	1000	10
Silicon-germanium	1800	10

TABLE 10-V. - TYPICAL MHD GENERATOR DESIGN PARAMETERS

Fluid	Peak temperature, $^\circ$F	Electrical conductivity, mhos/m	Velocity, ft/sec	Magnetic field strength, kG
Liquid metal	2000	1 000 000	300	10
Seeded gas	5000	10	5000	30
Seeded gas	3000	1.0	----	--
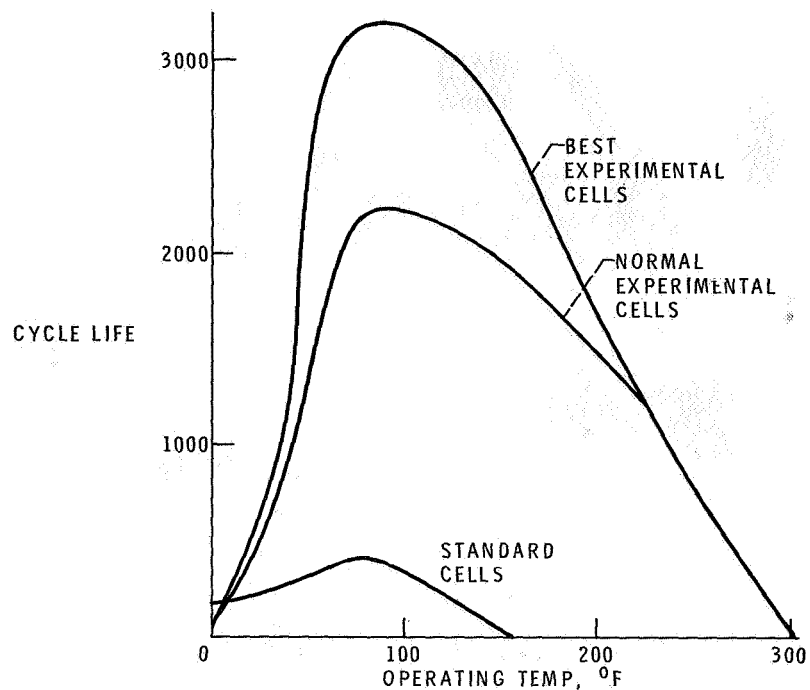
Figure 10-1. - Performance of experimental silver-zinc cell for 25 percent depth of discharge.
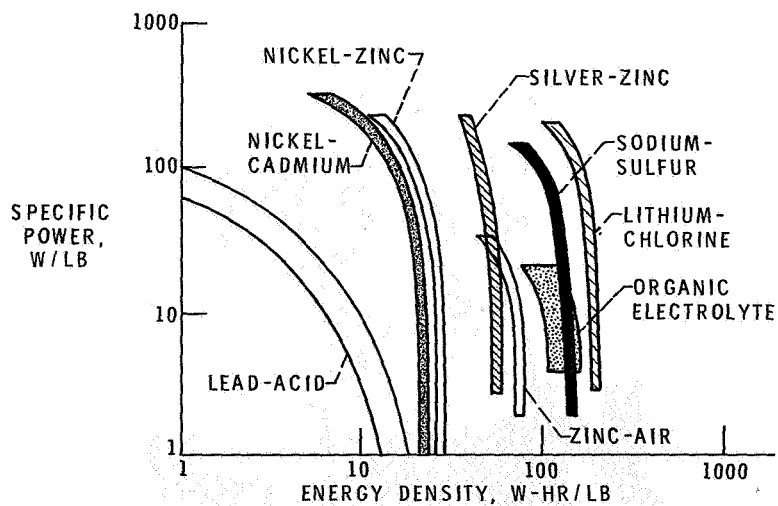
Figure 10-2. - Performance of batteries for electric vehicles. (Taken from 1967 Department of Commerce study: "The Automobile and Air Pollution".)
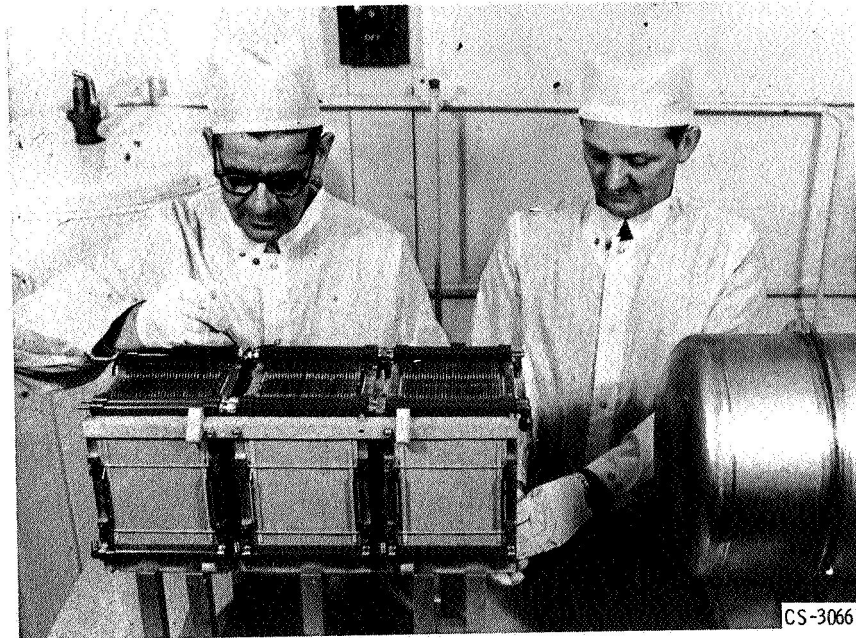
CS-30661

Figure 10-3. - Gemini fuel cell.
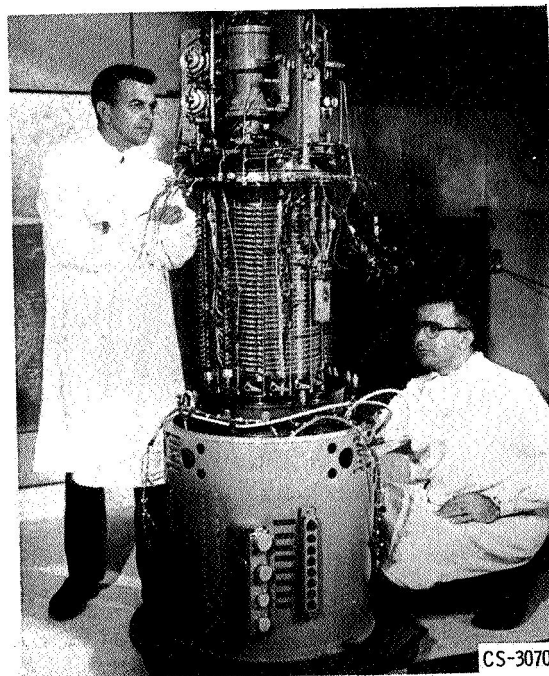
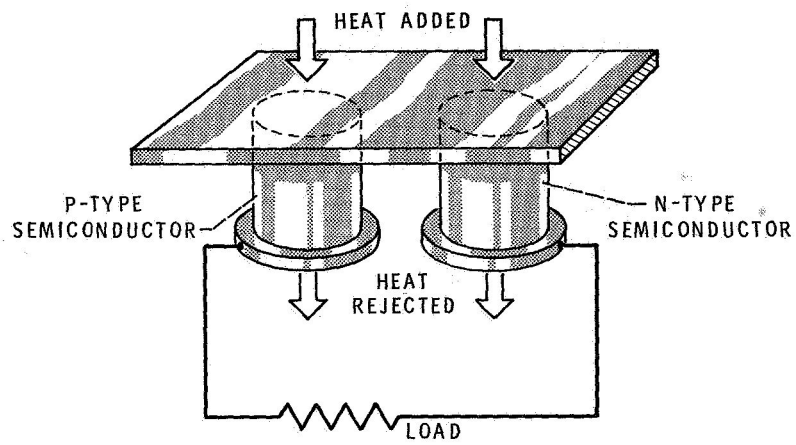CS-30701

Figure 10-4. - Apollo fuel cell.
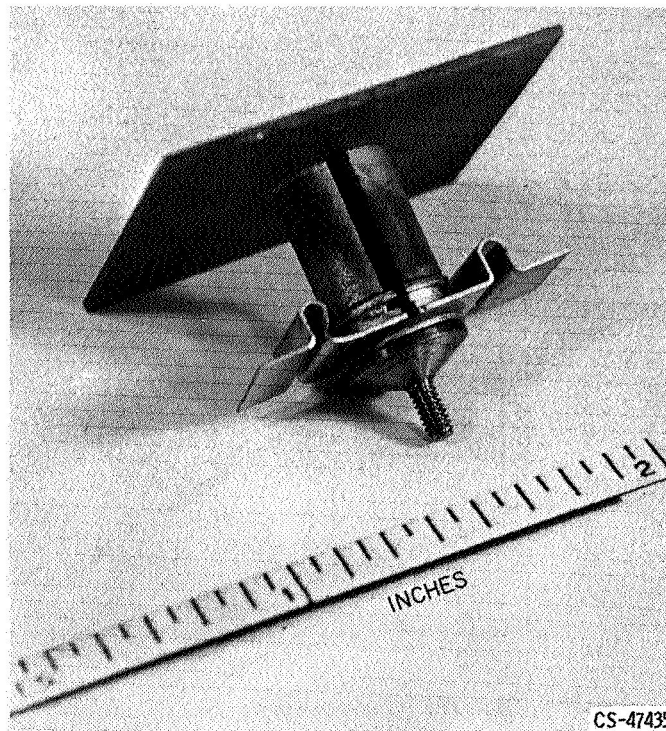
298

Figure 10-5. - Thermoelectric conversion.

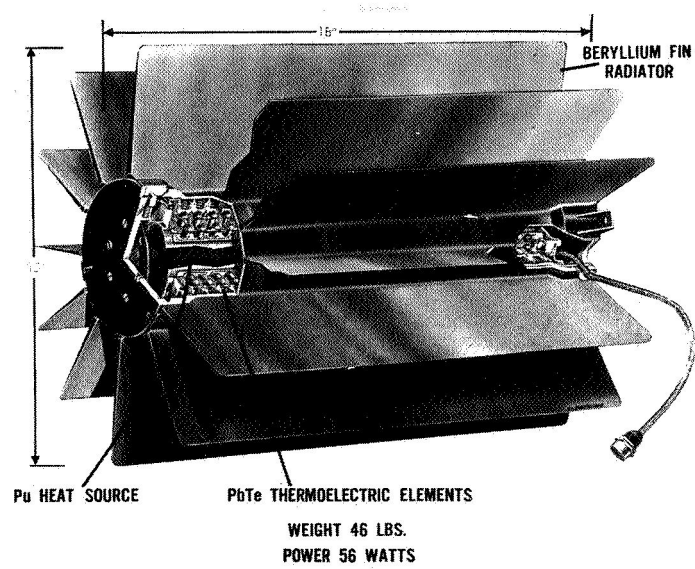

Figure 10-6. - Silicon-germanium thermoelectric couple.

BERYLLIUM FIN
RADIATOR

Pu HEAT SOURCE   PbTe THERMOELECTRIC ELEMENTS

WEIGHT 46 LBS.
POWER 56 WATTS

Figure 10-7. - SNAP-27 generator.   CS-40581

HOT EMITTER

HEAT
ADDED

COLD
COLLECTOR

⊖

⊕
Cs

HEAT
REJECTED

LOAD
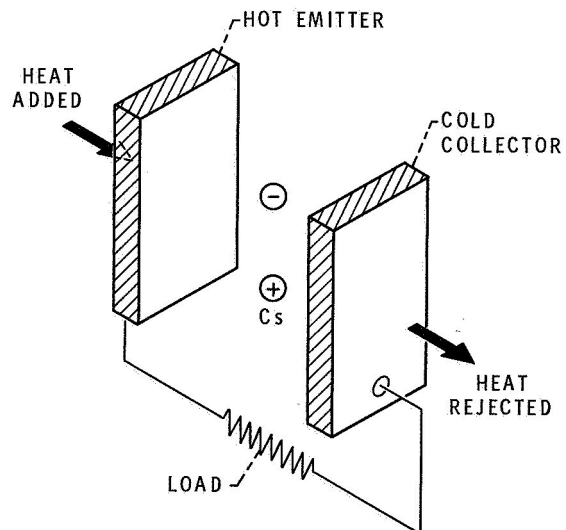
Figure 10-8. - Thermionic conversion.

300
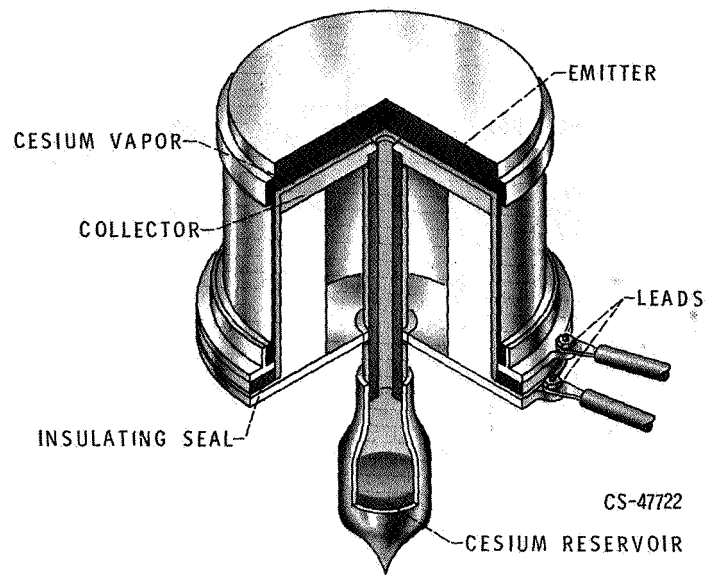
Figure 10-9. - Experimental thermionic converter.
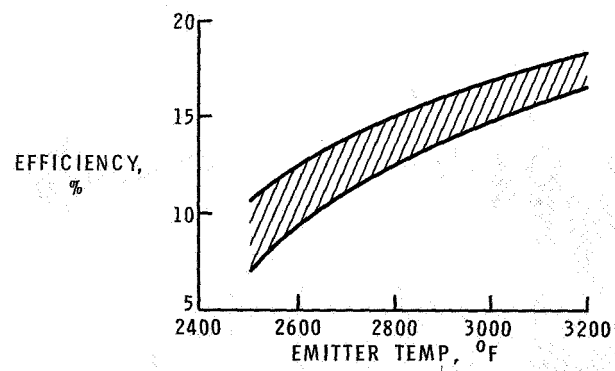
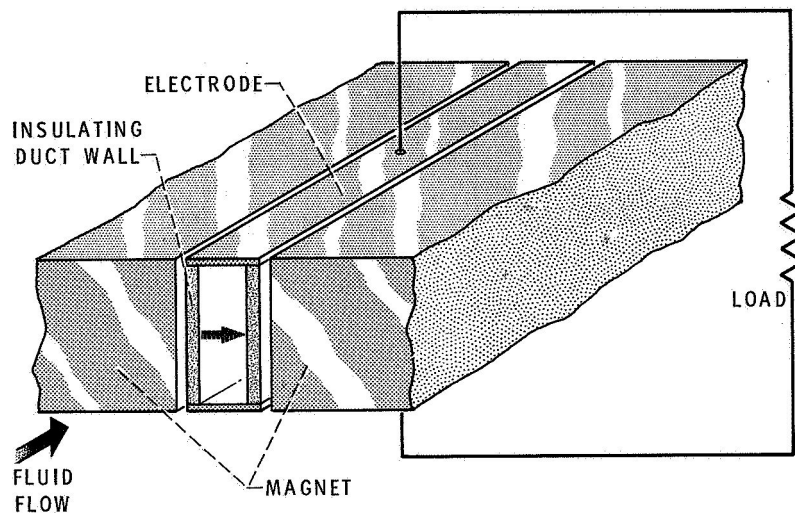Figure 10-10. - Thermionic conversion efficiency. Collector temperature, 1400° F.
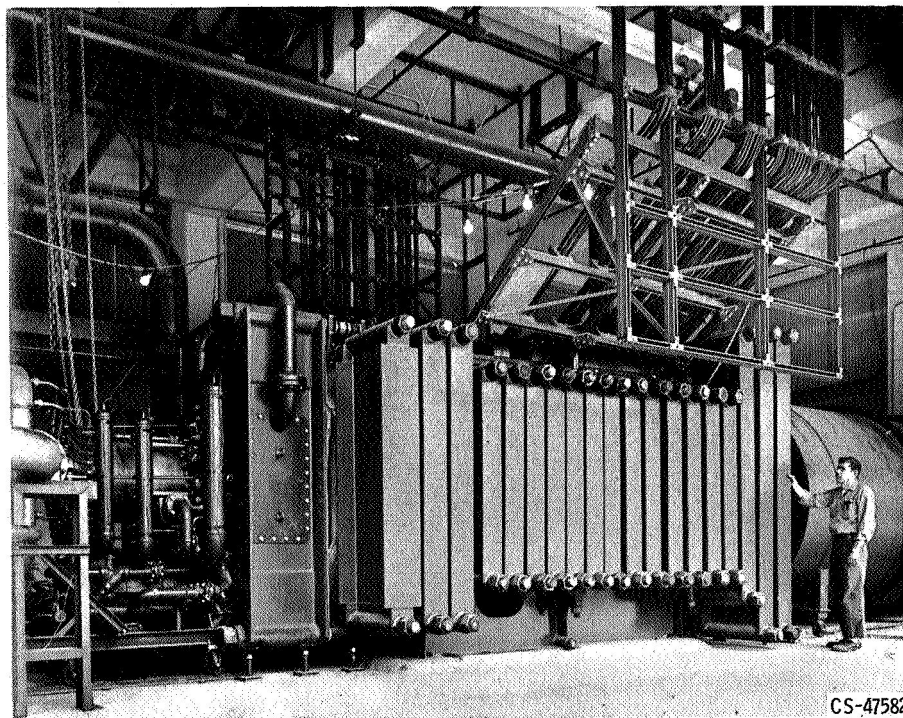
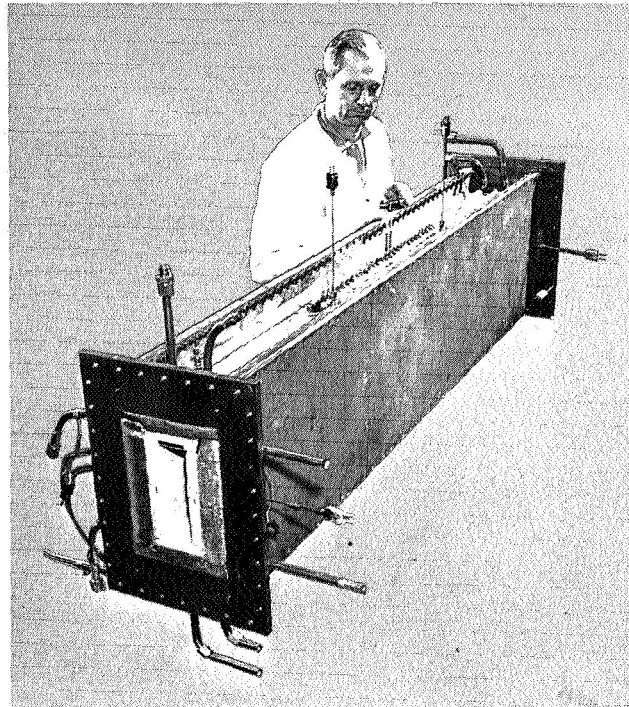Figure 10-11. - Magnetohydrodynamic (MHD) conversion.

Figure 10-12. - 23-Megawatt-electric combustion-fired MHD generator.

CS-47721

Figure 10-13. – 500-Kilowatt-electric argon MHD generator.